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USE OF SOURCE-REGION-STATION TIME CORRECTIONS AT NTS FOR DEPTH ESTIMATION

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Travel time residuals may be obtained from a least-squares location program which is run with the depth constrained to the known "true" value. When these residuals are used as travel-time corrections in the same program run depth-free, nearby events are located with smaller errors in depth. An elaboration of this technique has been denoted the SRST (Source-Region-Station-Time) technique by K. Veith. (cont on p 1473B)

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It is pointed ~~We point~~ out that the technique can be in serious error if deep earthquakes are used to determine residuals for shallow explosions in a source area where the earth structure between the earthquake and surface is different from that implied by the travel-time table used. It is also shown

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ABSTRACT

Travel time residuals may be obtained from a least-squares location program which is run with the depth constrained to the known "true" value. When these residuals are used as travel-time corrections in the same program run depth-free, nearby events are located with smaller errors in depth. An elaboration of this technique has been denoted the SRST (Source-Region-Station-Time) technique by K. Veith.

In this study we have applied the technique to Nevada Test Site (NTS) explosions. The mean estimated depth is changed from approximately 50 km to approximately 0 km with standard deviations of 30 km for a well-distributed 5-station network, and 20 km for a 9-station network.

We point out that the technique can be in serious error if deep earthquakes are used to determine residuals for shallow explosions in a source area where the earth structure between the earthquake and surface is different from that implied by the travel-time table used.

We also show that there is no evidence for change of travel-time residuals with time for arrivals from NTS at RKON, NPNT, BUL, and PRE. There is, however, evidence that significant changes in residuals are correlated with location at Pahute Mesa and that the changes may be due to interactions with a deep volcanic plug under Pahute Mesa.

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Positive determination of a seismic event as deep suffices to classify it as an earthquake, while if it can be definitely established that the event is shallow and if $(M_s - m_b)$ is small, then one may classify the event as an explosion with a small probability of error. Thus the problem of depth is of crucial importance in the positive discrimination of both earthquakes and explosions.

The most generally applicable technique for depth determination is by use of the Geiger location technique applied to the P wave arrival times. This method is, however, inaccurate for shallow depths because P waves propagated to teleseismic distances depart the source at almost vertical incidence. To make matters worse there are biases in depth estimation resulting from the use of incorrect travel time tables. See for example Flinn (1965), Evernden (1969), and Chiburis and Ahner (1970).

One approach to the problem, used by Evernden (1969), was to define a better regional travel-time distance relation by use of explosions of known depth. For 4 NTS explosions he was able by this technique to reduce the average depth from 39 to 12 kilometers. Evernden states that a similar result was achieved using earthquake data to derive an accurate travel-time table, but he does not say how he overcame the difficulties of unknown depth and origin time inherent in this approach.

In a related but slightly different technique, Evernden used improved travel-time tables, plus P_g estimates of origin time, to obtain an accurate location in latitude, longitude, and depth for the Fallon earthquake which was 40 km northeast of the SHOAL explosion. Using the residuals from this location for Fallon he was able to compute a depth of -1.7 km for SHOAL as contrasted to the known depth of +0.4 km.

Another technique suggested by Evernden was to use the residuals from master events whose <u>depth-free</u> locations gave the same answer as pP. However he goes on to say:

> "In practice, master station residuals have been computed against solutions restrained to the D(pP) values of depth."

Evernden used this approach in Kamchatka-Kurils, and found good agreement between pP and Geiger depths for new sample earthquakes. He also found that the master event had to be within 1°-3° of the event of interest.

Veith (1971, 1973, 1974, 1975) made a systematic practice of what the above quotation indicates Evernden felt he was forced to do. He called it the Source-Region-Station-Time (SRST) technique. Using events in Kamchatka-Kurils with good pP control, Veith constrained the events to the pP depth and then located the events in latitude and longitude. The residuals from the new location are then used to locate different nearby events depth-free. The results agree well with pP depths. Veith developed a computational technique which allows the method to be easily applied in practice. For each station the residuals for a suite of events with good pP depths covering the Kamchatka-Kuril region were contoured by fitting a polynomial to the measured values. In this way the residual for each station is allowed to vary in the proper way as different events are considered or as the event location shifts during convergence of the epicenter estimation process. An essential aspect of Veith's approach is also to use distance and azimuth-dependent station corrections.

Evernden (1969), however, provided an indication that this general approach can fail in critical applications:

> "There are conditions under which the use of earthquake data to control locations of explosions does not work. Thus, station correction factors computed for an Aleutian earthquake near Amchitka did not reduce the standard deviation of Longshot data, even though the earthquake was only about 1° from the Longshot explosion point. In other words, there was no correlation of Longshot residuals and residuals of a nearby shallow-focus Aleutian earthquake. The epicenter of the earthquake was south of the islands in the general area of the trench. Apparently, the marked contrast in crustal and shallow mantle characteristics between the two epicentral areas led to systematic differences in travel-time data."

We may note however that these same problems must have existed in Kamchatka-Kurils where plunging oceanic plates distort the travel-times but where Evernden and Veith had little trouble in obtaining the proper depth for earthquakes. Could not the problem be that residuals which are proper for even relatively shallow earthquakes (e.g. 30-60 km), may be

unsuitable for very shallow events? Consider the case of a region whose velocity-depth characteristic perfectly matches that used in deriving the travel-time table, except that the surficial 40 km have a low velocity. Then residuals obtained from earthquakes below 40 km will be zero and will therefore be incorrect for surface events. The P wave from a surface event to a distant station will arrive early relative to the arrival at a nearby station, since the vertically departing P wave spends less time in the low velocity surface layer. Thus the epicenter of a surface event will appear to be deep. As we shall see, the upper several hundred kilometers of the earth under NTS appear to have lower velocities than those implied in the Herrin 68 travel-time tables, so that NTS events are located too deep. Thus if deep NTS earthquakes existed and were used to determine SRST corrections, one would have the embarrassing situation of accurately locating all earthquakes but if an explosion occurred, one would calculate a substantial depth for it.

Although the above quote from Evernden (1969) might seem to indicate that he was aware of this trap, he nonetheless in the same paper presented a complete picture of accurate depth estimation in Kamchatka using the technique which he showed to fail for LONGSHOT. He apparently concluded that the failure was due to lateral changes in geology, and not to the fact that the earthquake and explosion were at different depths.

Since Veith found that near Kamchatka shallow events overlying deep events from which SRST corrections had been determined were located too shallow, we presume that the overlying strata had greater velocities than those below relative to the Herrin 68 Tables. We are presently studying a method of averaging the P and pP residuals from deep earthquakes to determine residuals which would be appropriate for surface events.

The main purpose of this report is to confirm Veith's procedures with a large data base of shallow events, i.e. explosions at NTS. In the course of the investigation it became clear that various subsidiary topics could be simultaneously discussed; and we have in fact investigated the variability of travel-time residuals as a function of time and space.

LOCATION RESULTS

As a test of the SRST technique discussed in the Introduction we have used the data developed by Chiburis and Ahner (1970). We have constrained the Pahute Mesa events to their known depths, used program HYPO to perform the Geiger location using only stations with $\Delta \geq 16°$, and averaged the residuals for each station. Stations at distances greater than 16° were selected in order to model the problem of interest, teleseismic location. Table I gives the mean Pahute Mesa Herrin 68 residual for each station together with the number of arrival time readings and the standard deviation of the population of residuals. Figure 1 is a map of the depth within 90° of NTS. The station numbers from Table I have been plotted next to one station location. Figure 2 is a map of NTS showing the general size of the Pahute Mesa test site. All of the events in this report have very few observations in the southwest teleseismic quadrant. Situations such as this are not without interest, however, since they frequently arise in the practical analysis of events in the USSR and China.

If a signal travels through a layer of thickness d, velocity V_1 at incidence angle i_o, then the differential travel time with respect to traveling through another layer of velocity V_2 is

$$\frac{(V_1-V_2)}{V_1V_2} \; \frac{d}{\cos i_o}.$$

Comparing the Basin and Range structure of Massé et al. (1972) to the average world-wide structure implicit in the Herrin tables, (Engdahl et al., 1968) we see that d=200 km, V_1=8.0 km/sec, V_2=7.5 km/sec are reasonable values. Since any small region such as NTS may have a regional correction, we may assume that the variation of residuals from NTS will vary as $1.7/\cos i_o(\Delta)$ + constant. The function $i_o(\Delta)$ is taken from Richter (1968), Appendix V, who assumed a surface velocity of 6.34 km/sec. Application of Snells law shows that $i_o(\Delta)$ will change insignificantly with respect to the present application if the velocity structure between 40 and 200 km is decreased from 8.0 to 7.5 km/sec.

The function $1.7/\cos i_o(\Delta)$+constant has been superimposed on the residuals from Table I plotted in Figure 3. We see that this formula accounts for the data trends rather well. The overall slope is in general agreement with the observations and the substantial cluster of large positive residuals around 20 degrees seems significant since it is at just this point that the theoretical curve is beginning to curve sharply up.

TABLE I

Mean Pahute Mesa SRST's for Shots Constrained to Known Depth but with Latitude and Longitude Unconstrained

	Station	Number of Observations	Average Residual	Standard Deviation of Observations
1	RK-ON	6	-1.2	.5
2	KC-MO	3	.5	.2
3	PG-BC	7	1.9	.6
4	FLO	5	.8	.1
5	JE-LA	1	1.8	-
6	OXF	5	1.7	.2
7	EU2AL	1	1.0	-
8	SHA	3	2.4	.2
9	CPO	4	0	.1
10	AX2AL	3	.9	.1
11	AAM	6	- .3	.5
12	WH2YK	5	.5	.3
13	ATL	4	.1	.1
14	BLA	5	.4	.2
15	BE-FL	1	.3	-
16	SCP	5	- .7	.3
17	CMC	5	- .4	.5
18	GEO	2	- .4	.1
19	OGD	2	- .3	.4
20	COL	8	.5	.5
21	LPS	4	1.1	.4
22	HN-ME	7	- .2	.2
23	SV3QB	6	-1.5	.2
24	NP-NT	5	.2	.4
25	GIE	1	1.1	-
26	GDH	3	.2	.2
27	SJG	7	.1	.2
28	CAR	5	.3	.3
29	NOR	3	-1.3	.5
30	TRN	4	-2.6	.4
31	KTG	3	- .4	.1
32	AKU	2	.5	0
33	NNA	1	- .7	-
34	ARE	4	.6	.5
35	KEV	1	-2.0	-
36	VAL	2	-1.0	.6
37	LPB	6	- .4	.2
38	ESK	2	-1.2	.2
39	OO-NW	1	- .9	-
40	KON	3	- .7	.7
41	NUR	4	-1.2	.3
42	COP	1	- .4	-
43	PTO	1	-1.7	-
44	MAT	3	.1	.3
45	TOL	3	- .6	.1
46	STU	2	- .4	.5
47	GG-GR	1	.2	-
48	PEL	3	- .6	.2
49	MAL	3	- .1	.1
50	SHK	2	.2	.1
51	SEO	4	.2	.6
52	WES	1	- .3	-
53	BEC	3	- .3	.1
54	GUA	3	-2.1	.9
55	SI-BC	3	1.8	1.0
56	ANT	2	.7	.3
57	TOR	1	-2.3	-
58	EN-MO	1	1.1	-
59	KIP	2	1.0	0

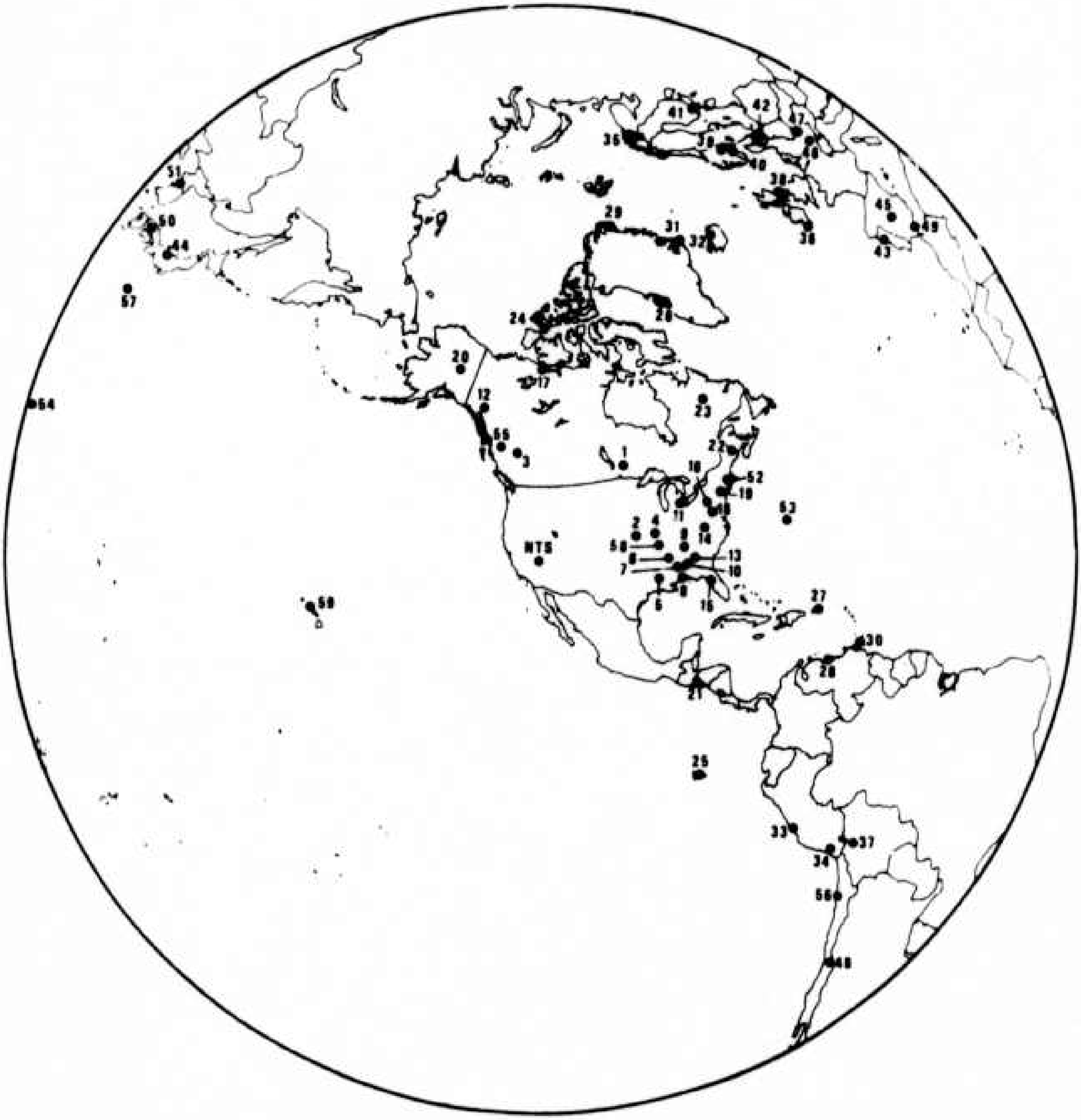

Figure 1. Location of stations used in this study. Station numbers act as keys to Table I.

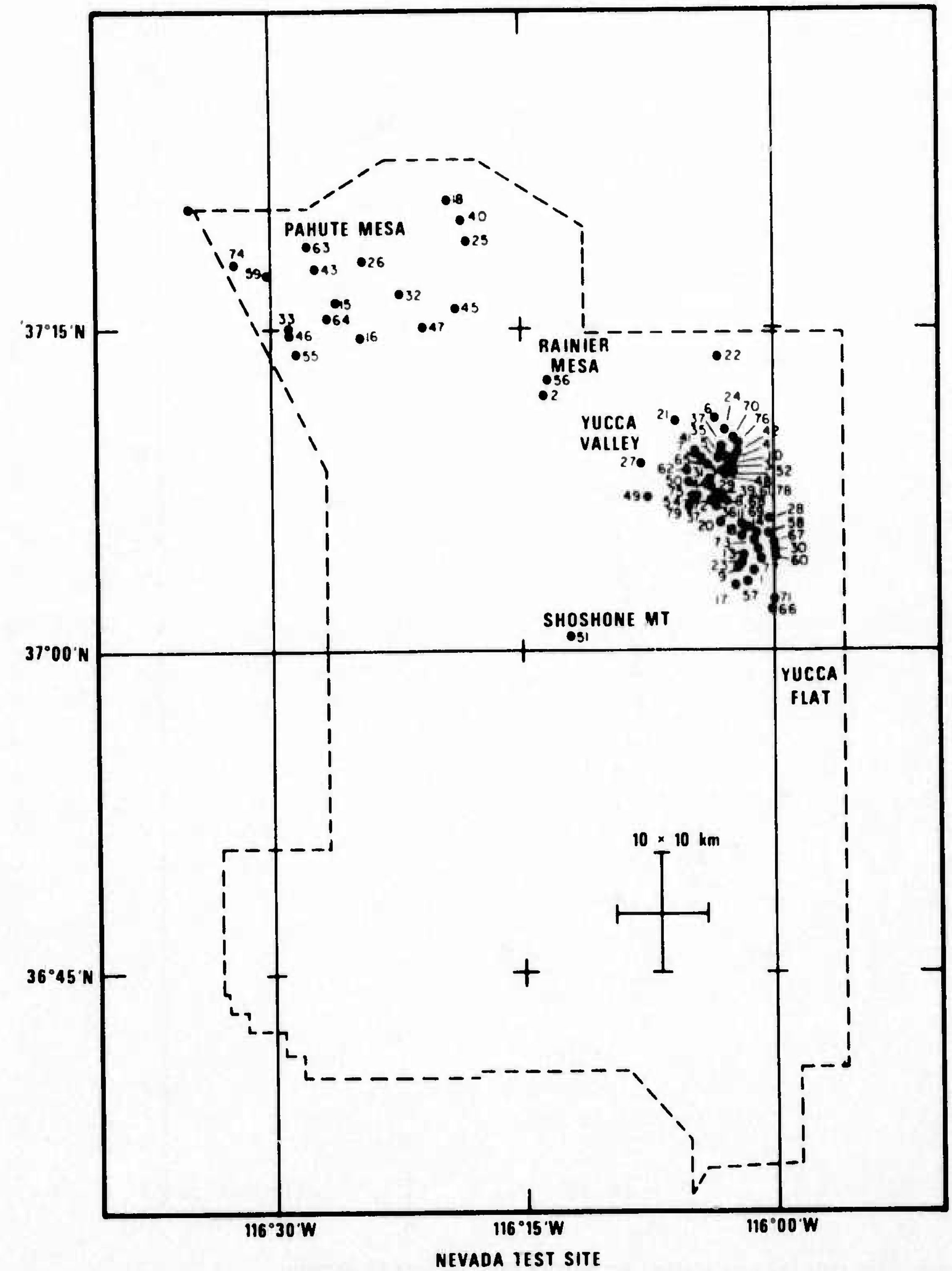

Figure 2. Locations of NTS Events.

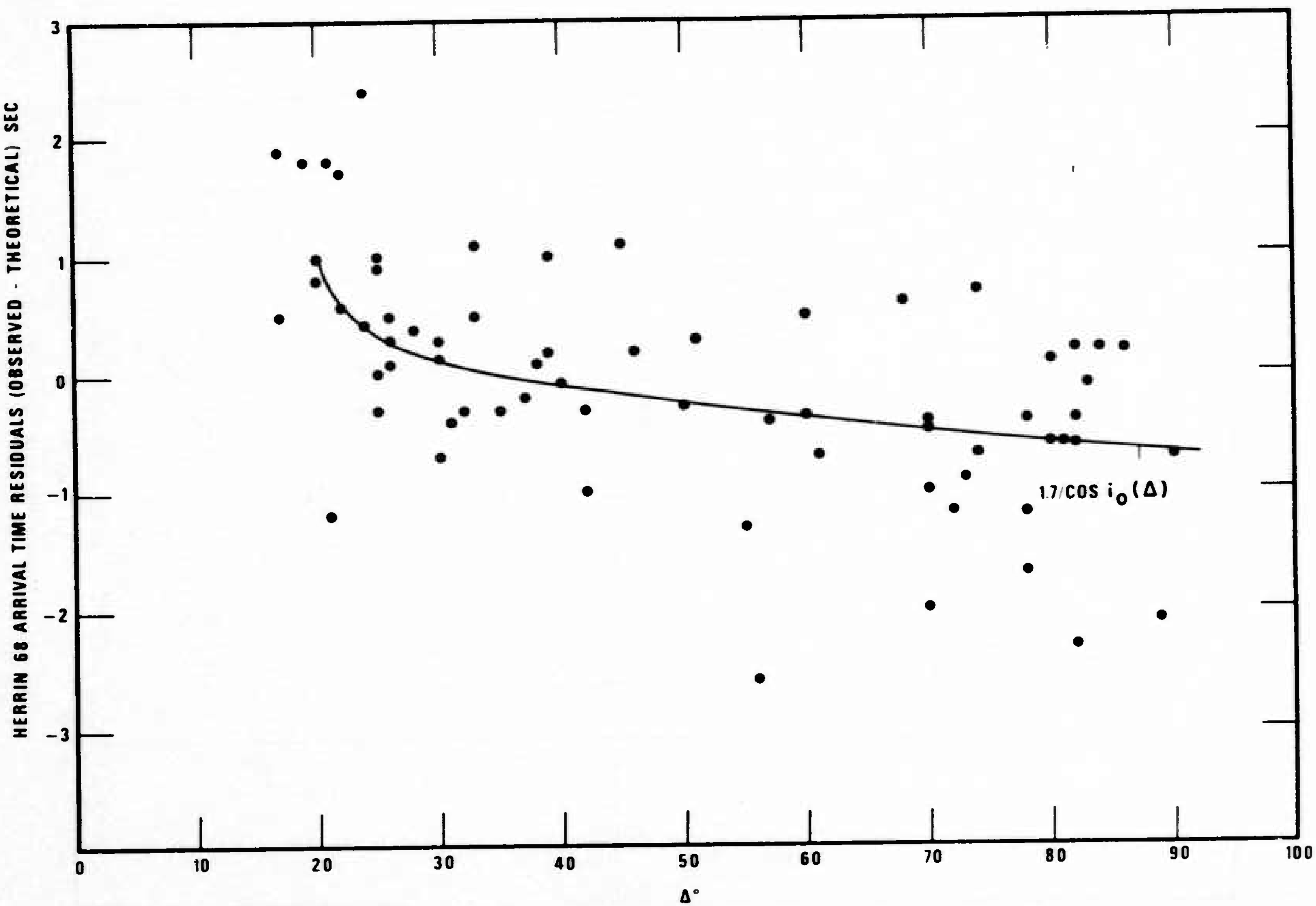

Figure 3. Herrin 68 average station residuals versus distance for Pahute Mesa events.

The average residuals in Table I were then applied to the eight Pahute Mesa events which were used to derive them; and to fourteen Yucca Flat events. These events are listed in Table II. The dates and origin times of these events and of several others to be discussed in the next section are given in Table IV. Because of our small source region, station corrections are not needed as a function of distance and azimuth and our procedure will therefore give results equally as good, in this case, as the more general procedures of Veith (1971, 1973, 1975).

From Table II we see that the average depth of Pahute Mesa events was reduced from 82 to 18 kilometers; while the average depth of Yucca Flat events was reduced from 64 to 6 kilometers. The LRSM and WWSSN data used is poorly distributed, typically for $\Delta > 25°$, 10 stations NE, 10 SE, 1 SW, 5 NW; for $16° < \Delta < 25°$, 4 NE, 0 SE, 0 SW, 1 NW.

All these events had a large number of reporting stations. In practice, however, many cases of interest are detected only at 5 or 6 stations. We have used the COMMODORE, GREELEY and TAN arrival time data to simulate this situation for some cases of interest.

We required first a well-distributed network of 5 stations, consisting of one in the distance range 16°-25° and in the Northeast quadrant; and four stations beyond $\Delta = 25°$, one in each quadrant. None of the outer four stations could be closer to each other in azimuth than 30°. Sets of stations meeting these criteria were selected at random from the COMMODORE data using a Monte Carlo technique; and locations were obtained without the use of SRST corrections using program SHIFT 360.

The mean resulting depth was 57 ± 19 (standard deviation of the population) km. Out of a total of 50 trials the minimum depth was 16 km and the maximum was 91. When SRST corrections were applied the mean depth decreased to 6 ± 24 km. The minimum was -46 km and the maximum was +49 km. When the random SRST runs were performed with readings from events GREELEY and TAN we found the results given in Table III.

The experiments with SRST's for all three explosions were repeated, allowing 4 more stations to detect beyond 25°. Without SRST corrections the mean depth for COMMODORE was 52 ± 13. The minimum was 27 km and the

TABLE II

Depths Resulting from use of Mean Pahute Mesa SRST's on Pahute Mesa and Yucca Valley Events Together with the Estimated Mean and Standard Deviation of the Sample Population

Event Name	Number of Stations used in Location Calculation	Depth Without SRST	Depth With SRST
		Pahute Events	
Rex	17	64	6
Duryea	20	80	20
Chartruse	31	92	19
Greeley	51	75	13
Scotch	26	67	1
Knickerbocker	20	100	36
Boxcar	17	68	22
Benham	12	107	25
		82±16	18±11
		Yucca Events	
Fore	27	36	-17
Klickitat	20	59	34
Turf	21	58	0
Wagtail	30	60	13
Cup	20	59	16
Buff	28	61	2
Dumont	39	84	0
Piledriver	37	59	1
Tan	39	70	7
Nash	20	65	- 7
Bourbon	17	80	7
Commodore	38	70	3
Auk	14	73	34
Corduroy	38	61	- 3
		64±12	6±14

TABLE III

Mean Depth and Standard Deviations of the Sample Population; Minimum and Maximum Depths Out of 50 Trial Locations using Observed Data in Randomly Selected, Well-Distributed Networks of 5 or 9 Stations; with and without SRST's

Number Stations	Base Event	Mean Depth and Standard Deviation for 50 Trials, km	Minimum Depth, km (50 Trials)	Maximum Depth, km (50 Trials)
		Without SRST		
5	Commodore	57 ± 19	16	91
9	Commodore	52 ± 13	27	73
		With SRST		
5	Commodore	6 ± 24	-46	+49
9	Commodore	2 ± 16	-22	+27
5	Greeley	15 ± 36	-98	+83
9	Greeley	-4 ± 33	-83	+36
5	Tan	-19 ± 41	-87	+44
9	Tan	-16 ± 20	-76	+16
5	Average	1 ± 33	-77	+58
9	Average	-6 ± 23	-60	+25

maximum 73 km. With SRST corrections for the average of all three explosions we obtained for the mean and standard deviation of the sample population 1 ± 33 km. for 5 stations and -6 ± 23 km for 9 stations.

These results suggest that, even with SRST's, depth estimation from teleseismic P arrival times will not be a reliable discriminant for events with estimated depths of less than, say, 50 km detected at less than 10 stations. It must be admitted, however, that the distribution of stations in these simulations is not ideal, and that a higher percentage of stations with $\Delta < 25°$ might help substantially.

STABILITY OF RESIDUALS

Table IV gives arrival times for NTS events at several stations. These data can be used to investigate the question of stability of travel-time residuals as a function of time. The possibility that residuals might vary as a function of time due to dilantancy has been suggested by Wyss (1973). We decided to measure the time of arrival of the first maximum. Illustrations of signals with good signal-to-noise ratios showing the picked arrival time are given in Figure 4. Since all the signals at a single station were in general quite smaller (except Pahute and Yucca to RKON as shown) these shapes were used as a visual "match filter" in order to allow the analyst to more accurately pick the arrival time for weak events. We have plotted times for core phases which because of their small angle of incidence can provide good control on depth. Both PRE recordings in Figure 4 show precursors which we have chosen to ignore in our analysis, picking instead the sharp arrival indicated.

Figure 5 illustrates the travel-time structure of Qamar (1973) in the vicinity of BUL and PRE. While it does not seem to provide an explanation for the precursors mentioned above, which arrive too long before the main energy, the Figure could be interpreted to explain some of the phasing after the arrivals we have picked. Figure 6 from Sweetser and Blandford (1973) shows that the amplitudes of these core phases are half a magnitude unit greater than those of P phases received at 90°, and thus are easily detected.

In Figure 7 we have plotted the Herrin-68 residual for events in the Yucca Valley to RKON, NPNT, BUL, and PRE. Generally, with the possible exception of late 1969, there appears to be no smooth variation with time, and there seems to be little correlation between the traces. Similar remarks seem to apply to the plots of the relative residuals in Figure 8.

The situation seems substantially different however when we plot the Herrin-68 residuals for events at Pahute Mesa. Here a very strong correlation is apparent between stations in both Figures 9 and 10. A test of the significance of event effects in the relative residuals was significant at

TABLE IV

Predicted and Observed Arrival Times for Events Used in this Report

				STATION BUL				STATION PRE				STATION RK-ON				STATION NP-NT			
Event Name	#	Date	Origin Time	Δ°	Predicted Arrival	Arrival	Q	Δ°	Predicted Arrival	Arrival	Q	Δ°	Predicted Arrival	Arrival	Q	Δ°	Predicted Arrival	Arrival	Q
Bilby	1	13 Sep 63	17:00:001	.92	17:19:387	17:19:251	G	.62	17:19:430	17:19:472	G	1.07	17:04:451	17:04:462	G	.32	17:07:297	17:07:318	G
Clearwater	2	16 Oct 64	17:00:001	1.03	17:19:387	17:19:394	G	.76	17:19:432	17:19:477	P	1.08	17:04:451	17:04:460	G	.18	17:07:284	17:07:305	G
Fore	3	16 Jan 64	16:00:001	.91	16:19:388	16:19:390	F	.63	16:19:431	16:19:475	P	1.02	16:04:447	16:04:456	G	.24	16:07:291	16:07:313	G
Klickitat	4	20 Feb 64	15:30:001	.90	15:49:387	15:49:388	F	.62	15:49:431	No Sig	-	1.01	15:34:446	15:34:456	G	.23	15:37:290	15:37:307	G
Turf	5	24 Apr 64	20:10:001	.92	20:29:387	20:29:390	P	.63	20:29:432	No Sig	-	1.02	20:14:447	20:14:458	G	.23	20:17:290	20:17:305	G
Bye	6	16 Jul 64	13:15:001	.91	13:34:387	No Sig	-	.63	13:34:432	No Sig	-	1.00	13:19:445	13:19:454	G	.19	13:22:287	13:22:307	P
Par	7	9 Oct 64	14:00:001	.93	14:19:388	14:19:393	P	.65	14:19:432	No Sig	-	1.03	14:04:448	14:04:461	G	.23	14:07:290	No Sig	-
Crepe	8	5 Dec 64	21:15:001	.93	21:34:388	21:34:393	P	.65	21:34:432	No Sig	-	1.03	21:19:450	21:19:461	G	.23	21:22:293	21:22:312	F
Wagtail	9	3 Mar 65	19:13:000	.93	19:32:387	19:32:390	G	.63	19:32:431	19:32:470	F	1.08	19:17:452	19:17:462	G	.31	19:20:296	19:20:315	G
Cup	10	26 Mar 65	15:34:081	.91	15:53:467	15:53:470	G	.62	15:53:511	15:53:554	F	1.02	15:38:526	15:38:534	G	.32	15:41:370	15:41:388	G
Bronze	11	23 Jul 65	17:00:000	.92	17:19:387	17:19:391	G	.62	17:19:430	17:19:472	G	1.05	17:04:449	17:04:458	G	.28	17:07:294	17:07:312	G
Charcoal	12	10 Sep 65	17:12:000	.91	17:31:386	17:31:392	G	.61	17:31:430	No Film	-	1.05	17:16:450	17:16:460	G	.30	17:19:295	17:19:313	G
Buff	13	16 Dec 65	19:15:000	.92	19:34:387	19:34:390	F	.62	19:34:430	19:34:472	G	1.07	19:19:451	19:19:460	G	.30	19:22:296	19:22:316	G
Lampblack	14	18 Jan 66	18:35:000	.91	18:54:386	18:54:387	G	.61	18:54:430	18:54:470	F	1.05	18:39:449	18:39:458	G	.29	18:42:294	18:42:311	G
Rex	15	24 Feb 66	15:55:070	1.16	16:14:460	16:14:465	P	.90	16:14:504	No Sig	-	1.14	15:59:527	15:59:536	F	.10	16:02:347	16:02:369	G
Duryea	16	14 Apr 66	14:13:431	1.17	14:33:221	14:33:224	G	.91	14:33:265	No Sig	-	1.16	14:18:291	14:18:298	G	.13	14:21:111	14:21:132	P
Cyclamen	17	5 May 66	14:00:000	.94	14:19:387	No Sig	-	.63	14:19:431	No Sig	-	1.09	14:04:453	14:04:466	F	.33	14:07:297	14:07:318	G
Chartruse	18	6 May 66	15:00:000	1.05	15:19:388	15:19:393	G	.80	15:19:432	15:19:468	F	1.02	15:04:445	15:04:458	G	.03	15:07:271	15:07:294	G
Piranha	19	13 May 66	13:30:000	.92	13:49:387	13:49:390	G	.62	13:49:430	No Film	-	1.06	13:34:450	13:34:460	G	.29	13:37:294	13:37:314	G
Dumont	20	19 May 66	13:56:281	.93	14:16:068	14:16:071	G	.64	14:16:112	No Film	-	1.05	14:01:130	14:01:140	G	.27	14:03:573	14:03:596	G
Discus	21	27 May 66	20:00:000	.94	20:19:386	20:19:390	P	.66	20:19:430	No Sig	-	1.02	20:04:445	20:04:457	G	.20	20:07:286	20:07:306	G
Piledriver	22	2 Jun 66	15:30:000	.89	15:49:385	15:49:388	G	.62	15:49:429	No Film	-	.97	15:34:439	15:34:448	F	.15	15:37:282	15:37:301	G
Tan	23	3 Jun 66	14:00:000	.93	14:19:387	14:19:390	G	.63	14:19:431	14:19:474	G	1.07	14:04:451	14:04:460	G	.31	14:07:296	14:07:314	G
Kankakee	24	15 Jun 66	18:02:471	.90	18:22:257	18:22:257	P	.62	18:22:301	No Sig	-	1.00	18:07:315	18:07:322	G	.21	18:10:158	18:10:176	G
Halfbeak	25	30 Jun 66	22:15:000	1.05	22:34:388	22:34:390	G	.79	22:34:432	22:34:476	G	1.03	22:19:446	22:19:457	G	.06	22:22:298	No Pick	-
Greeley	26	20 Dec 66	15:30:000	1.13	15:49:387	No Film	-	.88	15:49:434	15:49:474	G	1.10	15:34:454	15:34:463	F	.07	15:37:278	15:37:294	P
Nash	27	19 Jan 67	16:45:001	.98	17:04:388	No Film	-	.69	17:04:432	17:04:472	F	1.07	16:49:451	16:49:462	G	.23	16:52:290	16:52:310	G
Bourbon	28	20 Jan 67	17:40:034	.89	17:59:420	No Film	-	.60	17:59:464	17:59:500	F	1.03	17:44:481	17:44:491	G	.28	17:47:327	17:47:346	G
Agile	29	23 Feb 67	18:50:000	.93	19:09:386	No Film	-	.64	19:09:431	19:09:473	G	1.05	18:54:448	No Pick	-	.25	18:57:291	18:57:310	G
Mickey	30	10 May 67	13:40:000	.89	13:59:386	13:59:390	F	.59	13:59:430	Poor Start	-	1.04	13:44:448	13:44:458	G	.30	13:47:295	13:47:314	G
Commodore	31	20 May 67	15:00:000	.93	15:19:387	15:19:390	G	.64	15:19:431	15:19:473	G	1.04	15:04:448	15:04:459	G	.25	15:07:291	15:07:310	G
Scotch	32	23 May 67	14:00:000	1.11	14:19:389	14:19:395	G	.85	14:19:433	14:19:474	F	1.10	14:04:454	14:04:464	F	.10	14:07:278	14:07:298	G
Knickerbocker	33	26 May 67	15:00:015	1.20	15:19:405	15:19:411	F	.94	15:19:450	Poor Start	-	1.18	15:04:477	15:04:484	F	.12	15:07:294	15:07:315	G
Stanley	34	27 Jul 67	13:00:000	.91	13:19:386	13:19:389	P	.62	13:19:430	No Sig	-	1.02	13:04:446	13:04:457	G	.23	13:07:289	13:07:310	G
Yard	35	7 Sep 67	13:45:000	.91	14:04:386	14:04:390	F	.63	14:04:430	Poor Start	-	1.02	13:49:446	13:49:456	G	.22	13:52:289	13:52:310	G
Zaza	36	27 Sep 67	17:00:000	.93	17:19:387	17:19:390	G	.64	17:19:431	17:19:472	G	1.06	17:04:450	17:04:459	G	.28	17:07:293	17:07:312	G
Lanpher	37	18 Oct 67	14:30:000	.93	14:49:387	14:49:390	G	.64	14:49:431	14:49:474	G	1.05	14:34:449	14:34:459	G	.26	14:37:292	14:37:317	G
Staccato	38	19 Jan 68	15:00:000	.91	15:19:386	No Film	-	.63	15:19:430	No Sig	-	1.02	15:04:445	15:04:457	P	.22	15:07:289	15:04:308	P
Knox	39	21 Feb 68	15:30:000	.93	15:49:387	15:49:390	G	.63	15:49:431	15:49:474	G	1.05	15:34:449	15:34:458	G	.26	15:37:292	15:37:311	G
Stinger	40	22 Mar 68	15:00:000	1.05	15:19:388	15:19:395	G	.80	15:19:432	15:19:478	G	1.03	15:04:445	15:04:457	G	.04	15:07:273	15:07:294	G
Noor	41	10 Apr 68	14:00:000	.93	14:19:386	No Sig	-	.65	14:19:430	No Sig	-	1.03	14:04:446	14:04:459	G	.22	14:07:288	14:07:310	G
Shuffle	42	18 Apr 68	14:05:000	.90	14:24:386	14:24:387	G	.61	14:24:430	Poor Start	-	1.01	14:09:445	14:09:455	G	.22	14:12:289	14:12:308	G
Boxcar	43	26 Apr 68	15:00:000	1.17	15:19:390	15:19:393	G	.92	15:19:435	15:19:477	G	1.13	15:04:458	15:04:466	G	.07	15:07:278	15:07:294	F
Clarks	44	17 May 68	13:00:000	.93	13:19:387	No Film	-	.64	13:19:431	13:19:482	P	1.05	13:04:449	13:04:459	G	.26	13:07:292	13:07:311	G
Rickey	45	15 Jun 68	13:59:599	1.07	14:19:386	14:19:394	G	.81	14:19:432	No Film	-	1.08	14:04:451	14:04:462	G	.11	14:07:277	14:07:299	G
Chateaugay	46	28 Jun 68	12:22:000	1.21	12:49:390	12:49:395	G	.95	12:41:435	No Film	-	1.18	12:26:462	12:26:471	G	.12	12:29:280	12:29:301	F
Sled	47	29 Aug 68	22:45:000	1.10	23:04:388	23:04:395	G	.84	23:04:432	23:04:479	G	1.11	22:49:454	22:49:464	G	.12	22:52:279	22:52:301	P
Noggin	48	6 Sep 68	14:00:001	.91	14:19:387	14:19:390	G	.62	14:19:431	14:19:475	G	1.03	14:04:448	14:04:456	G	.24	14:07:291	14:07:310	G
Stoddard	49	17 Sep 68	14:19:388	.98	14:19:388	14:19:390	P	.69	14:19:432	No Sig	-	1.08	14:04:453	14:04:463	G	.26	14:07:292	14:07:311	G
Crew	50	4 Nov 68	15:15:000	.95	15:34:387	15:34:388	P	.66	15:34:431	No Sig	-	1.05	15:19:449	15:19:460	G	.25	15:22:291	15:22:310	G
Mingvase	51	20 Nov 68	18:00:000	1.08	18:19:389	18:19:390	P	.77	18:19:433	No Sig	-	1.21	18:04:466	18:04:478	G	.36	18:07:301	18:07:320	F
Tinderbox	52	22 Nov 68	16:19:000	.91	16:38:386	No Sig	-	.62	16:38:430	No Sig	-	1.02	16:23:446	16:23:456	G	.24	16:26:290	No Sig	-
Schooner	53	8 Dec 68	16:00:001	1.24	16:19:393	16:19:400	F	.99	16:19:437	No Sig	-	1.16	16:04:461	16:04:472	F	.03	16:07:273	16:07:298	F
Tyg	54	12 Dec 68	15:10:000	.94	15:29:386	15:29:390	P	.65	15:29:430	No Sig	-	1.06	15:14:449	15:14:461	F	.26	15:17:291	15:17:310	P
Benham	55	19 Dec 68	16:30:000	1.20	16:49:393	16:49:391	G	.94	16:49:438	16:49:473	G	1.19	16:34:466	16:34:470	G	.14	16:37:284	16:37:293	F
Wineskin	56	15 Jan 69	19:30:000	1.03	19:49:388	19:49:390	G	.75	19:49:433	19:45:475	G	1.07	19:34:451	19:34:462	G	.17	19:37:284	19:37:304	G
Vise	57	30 Jan 69	15:00:000	.93	15:19:387	15:19:390	P	.63	15:19:431	No Sig	-	1.08	15:04:452	15:04:463	G	.32	15:07:297	15:07:317	G
Thistle	58	30 Apr 69	17:00:000	.90	17:19:386	17:19:386	G	.60	17:19:430	17:19:473	F	1.04	17:04:448	17:04:458	G	.29	17:07:294	17:07:313	G
Purse	59	7 May 69	13:45:000	1.21	14:04:390	14:04:394	F	.95	14:04:435	14:04:479	G	1.17	13:49:460	13:49:469	G	.09	13:52:276	13:52:299	G
Torrido	60	27 May 69	14:15:000	.90	14:34:386	14:34:387	P	.60	14:34:430	No Sig	-	1.05	14:19:449	14:19:458	G	.30	14:22:296	14:22:315	G
Ildrim	61	16 Jul 69	13:02:300	.93	13:22:087	13:22:089	P	.63	13:22:131	No Sig	-	1.05	13:07:148	13:07:159	G	.26	13:09:592	13:10:012	G
Hutch	62	16 Jul 69	14:55:000	.94	15:14:387	15:14:389	G	.66	15:14:431	15:14:474	F	1.05	14:59:449	14:59:460	G	.24	15:02:290	15:02:310	G
Jorum	63	16 Sep 69	14:30:000	1.17	14:49:390	14:49:390	G	.92	14:49:435	14:49:476	G	1.12	14:34:456	14:34:465	G	.06	14:37:274	14:37:295	F
Pipkin	64	8 Oct 69	14:30:001	1.17	14:49:391	14:49:392	G	.91	14:49:435	14:49:480	F	1.15	14:34:460	14:34:470	G	.11	14:37:280	14:37:301	G
Calabash	65	29 Oct 69	22:01:514	.93	22:21:301	22:21:295	G	.64	72:21:345	No Film	-	1.03	22:06:361	22:06:368	G	.23	22:09:204	22:09:219	G
Piccalalilli	66	21 Nov 69	14:52:000	.91	15:11:386	15:11:386	P	.61	15:11:430	No Sig	-	1.08	14:56:452	14:56:462	G	.35	14:59:299	14:59:319	G
Grape A	67	17 Dec 69	15:00:000	.91	15:19:386	15:19:385	G	.60	15:19:430	15:19:471	G	1.04	15:04:448	15:04:457	G	.29	15:07:295	15:07:314	G
Terrine	68	18 Dec 69	19:00:000	.92	19:19:387	19:19:385	F	.63	19:19:431	19:19:472	F	1.04	19:04:448	19:04:456	G	.26	19:07:292	19:07:310	G
Grape B	69	4 Feb 70	17:00:000	.91	17:19:386	17:19:388	G	.62	17:19:430	17:19:472	G	1.05	17:04:449	17:04:458	G	.28	17:07:294	No Pick	-
Labis	70	5 Feb 70	15:00:000	.90	15:19:386	15:19:395	P	.61	15:19:430	No Sig	-	1.00	15:04:444	15:04:454	G	.21	15:07:288	No Pick	-
Cumarin	71	25 Feb 70	14:28:380	.91	14:48:166	14:48:165	P	.61	14:48:210	No Sig	-	1.08	14:33:232	14:33:241	G	.34	14:36:079	14:36:099	G
Yannigan	72	26 Feb 70	15:30:000	.93	15:49:387	15:49:388	P	.64	15:49:431	No Sig	-	1.05	15:34:449	15:34:460	G	.26	15:37:292	15:37:312	G
Shaper	73	23 Mar 70	23:05:000	.91	23:24:386	23:24:386	G	.61	23:24:430	23:24:471	G	1.05	23:09:449	23:09:458	G	.29	23:12:295	23:12:313	G
Handley	74	26 Mar 70	19:00:002	1.23	19:19:394	19:19:393	G	.98	19:19:438	19:19:479	G	1.17	19:04:464	19:04:470	G	.07	19:07:278	19:07:296	F
Can	75	21 Apr 70	15:00:000	.95	15:19:387	15:19:387	P	.65	15:19:431	No Sig	-	1.06	15:04:450	15:04:460	G	.26	15:07:292	15:07:311	F
Cornice	76	15 May 70	13:30:000	.90	13:49:386	13:49:389	P	.61	15:49:430	No Sig	-	1.00	13:34:444	13:34:455	G	.22	13:37:288	13:37:308	G
Morrones	77	21 May 70	14:15:000	.91	14:34:386	14:34:385	P	.61	14:34:430	No Sig	-	1.06	14:19:450	14:19:450	G	.31	14:22:300	14:22:314	G
Flask	78	26 May 70	15:00:000	.93	15:19:387	15:19:386	G	.64	15:19:431	15:19:473	G	1.05	15:04:449	15:04:460	G	.26	15:07:292	15:07:310	G
Arnica	79	26 Jun 70	13:00:000	.95	13:19:386	No Sig	-	.66	13:19:430	No Sig	-	1.07	13:04:450	13:04:462	F	.26	13:07:291	No Pick	-

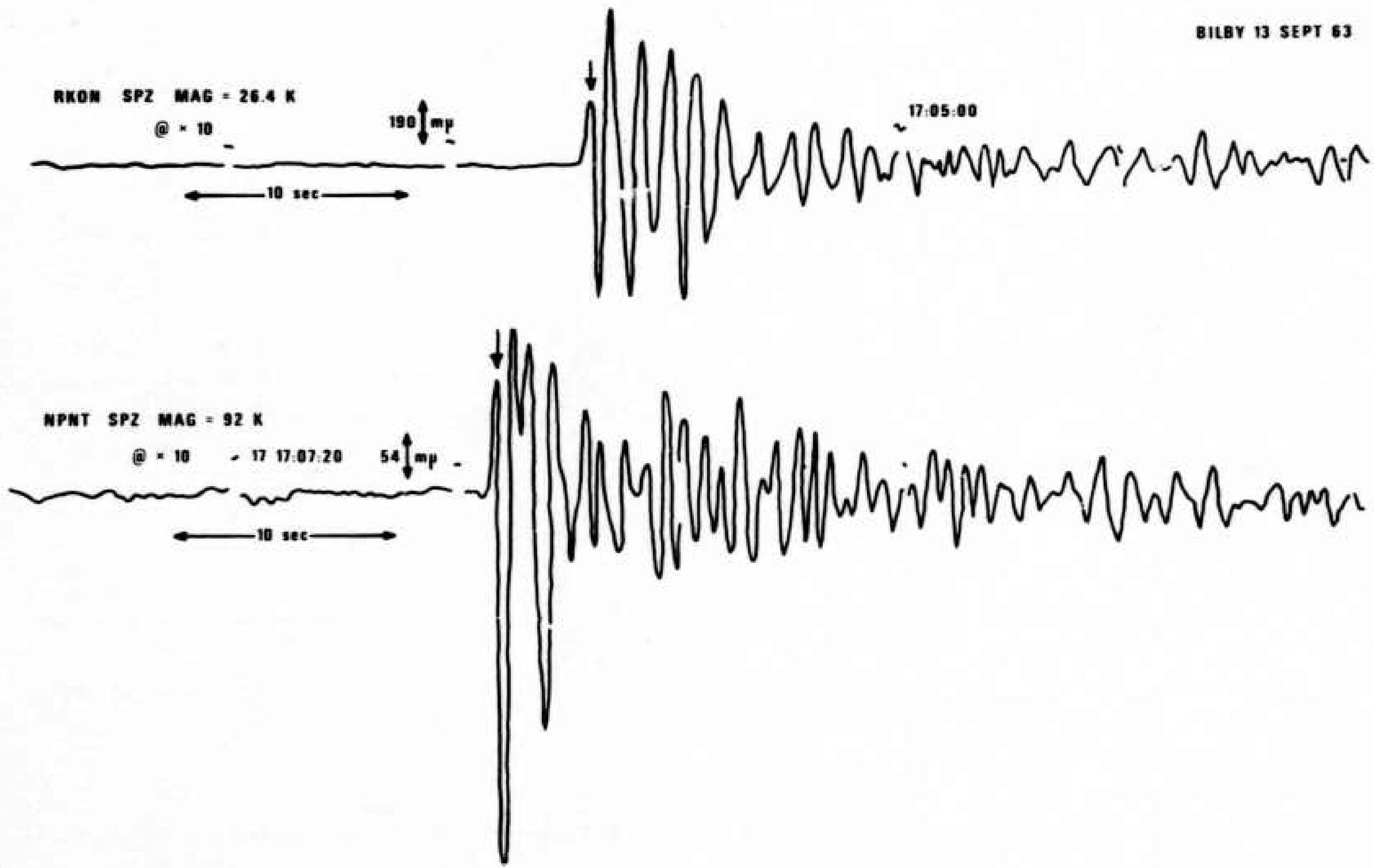

Figure 4. Tracings of P or PKP arrivals from NTS at RKON, BUL, PRE.

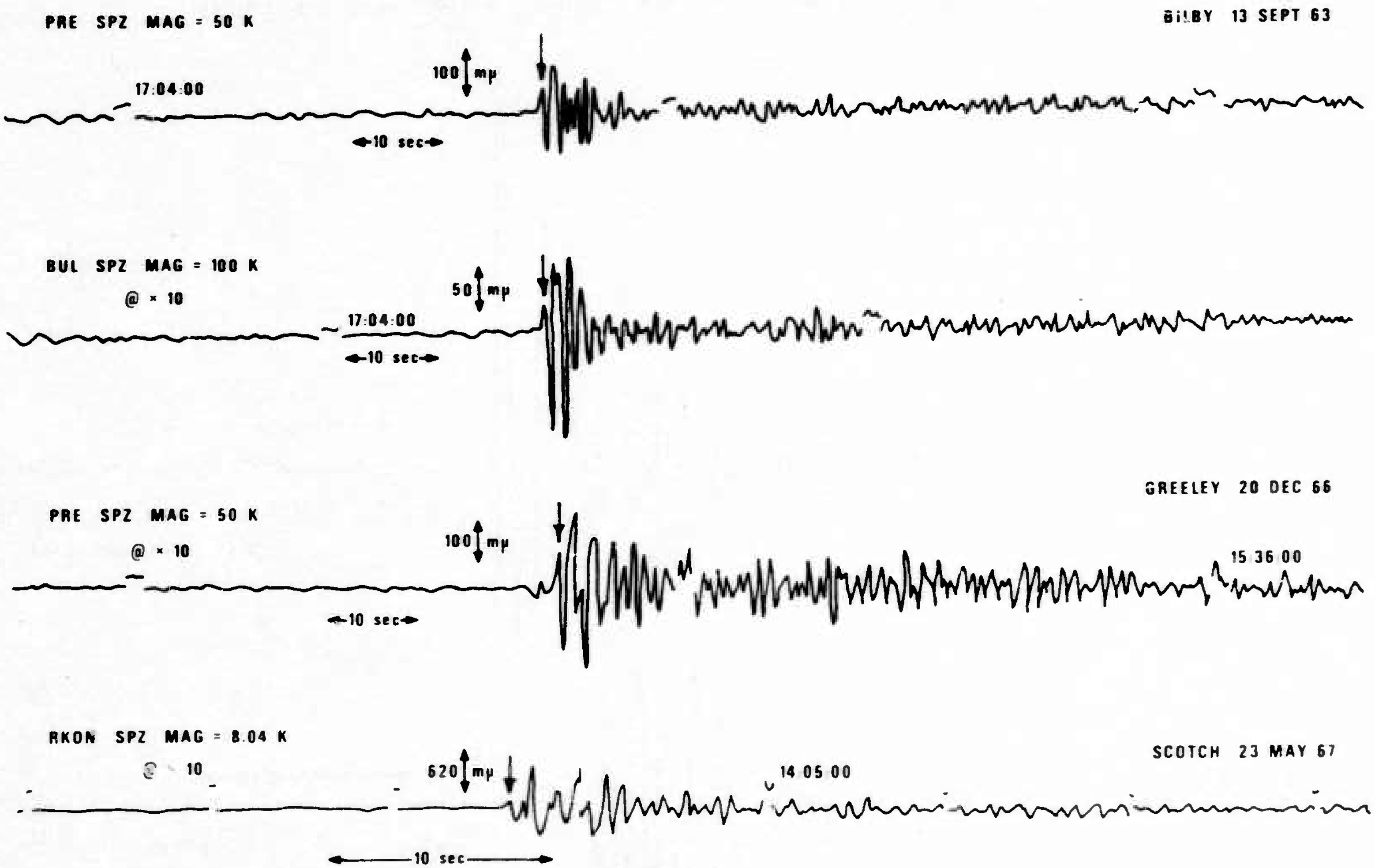

Figure 4 continued. Tracings of P or PKP arrivals from NTS at RKON, BUL, PRE.

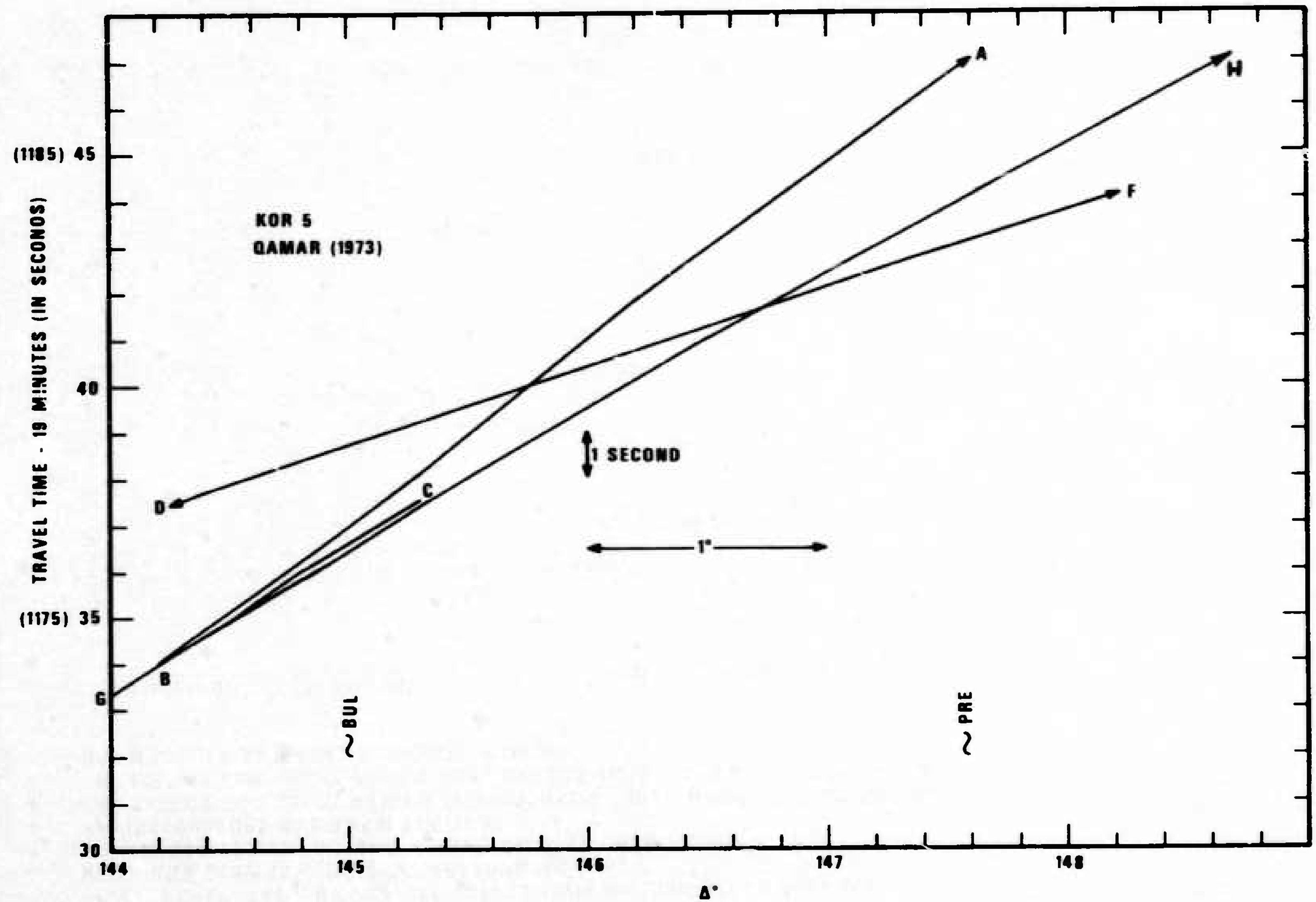

Figure 5. Core-phase travel times, from Qamar (1973).

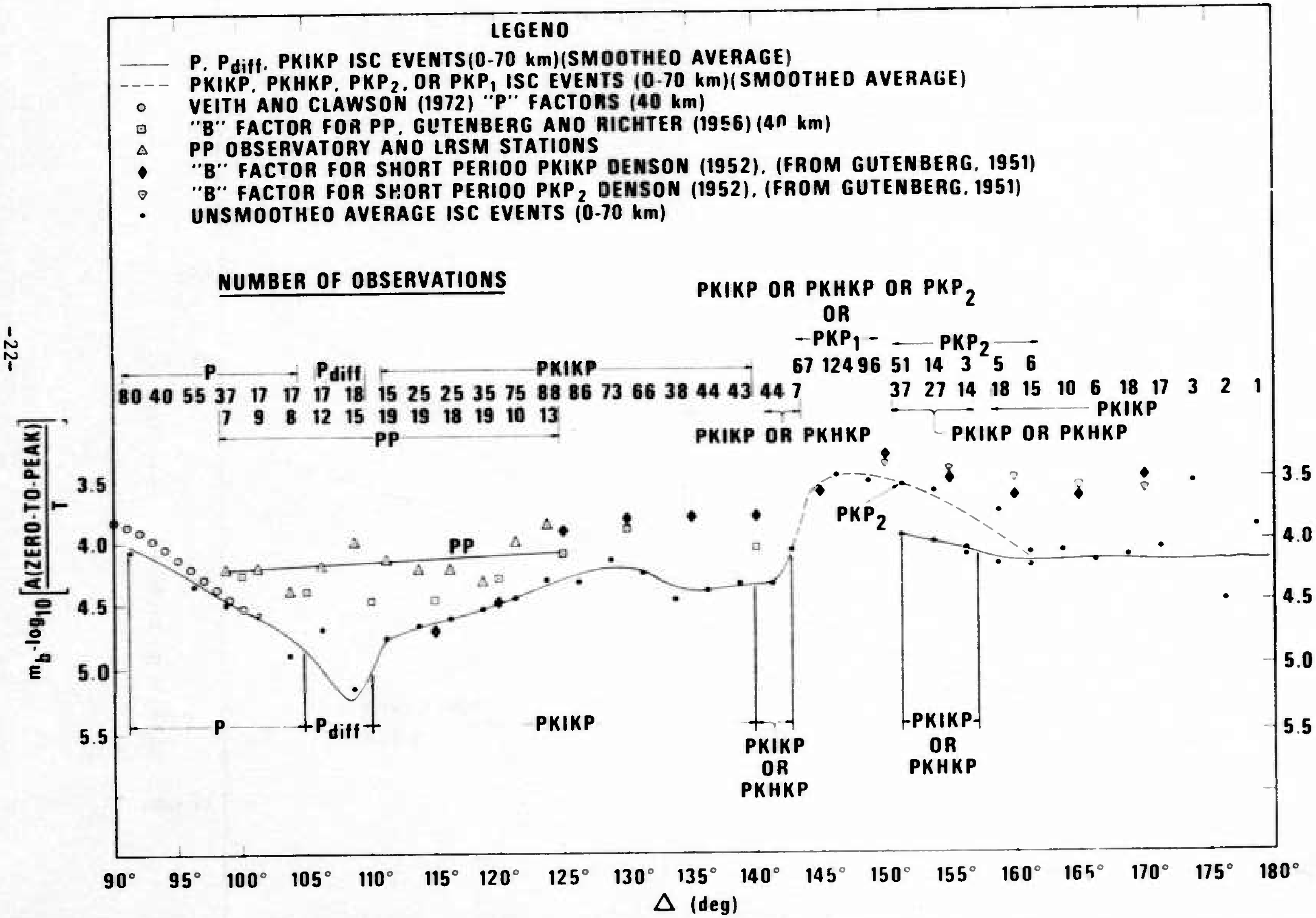

Figure 6. Average amplitude versus distance curves from ISC event data (90°-180°), from Sweetser and Blandford,(1973).

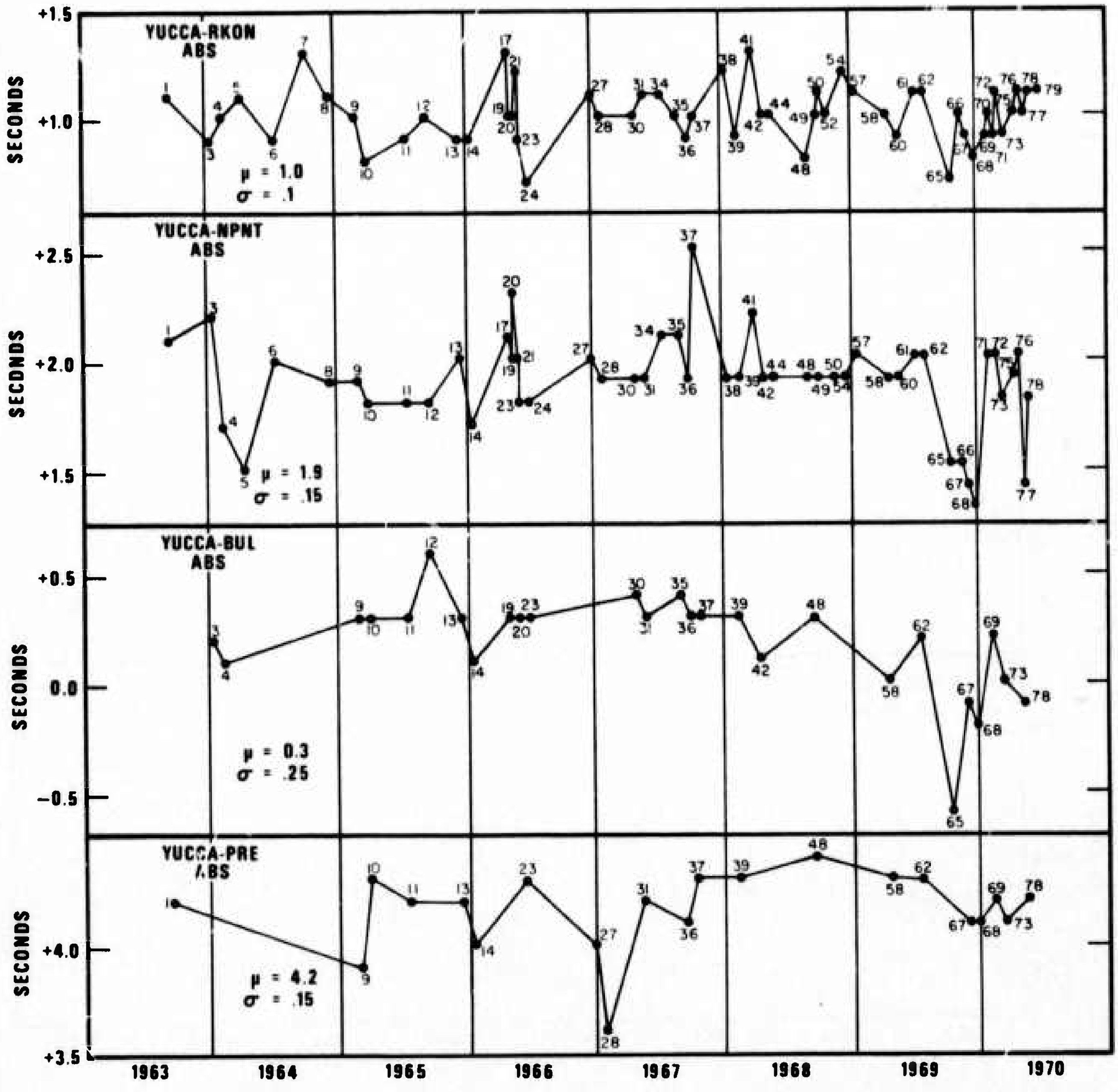

Figure 7. Yucca to RKON, NPNT, BUL, PRE, absolute Herrin-68 residuals.

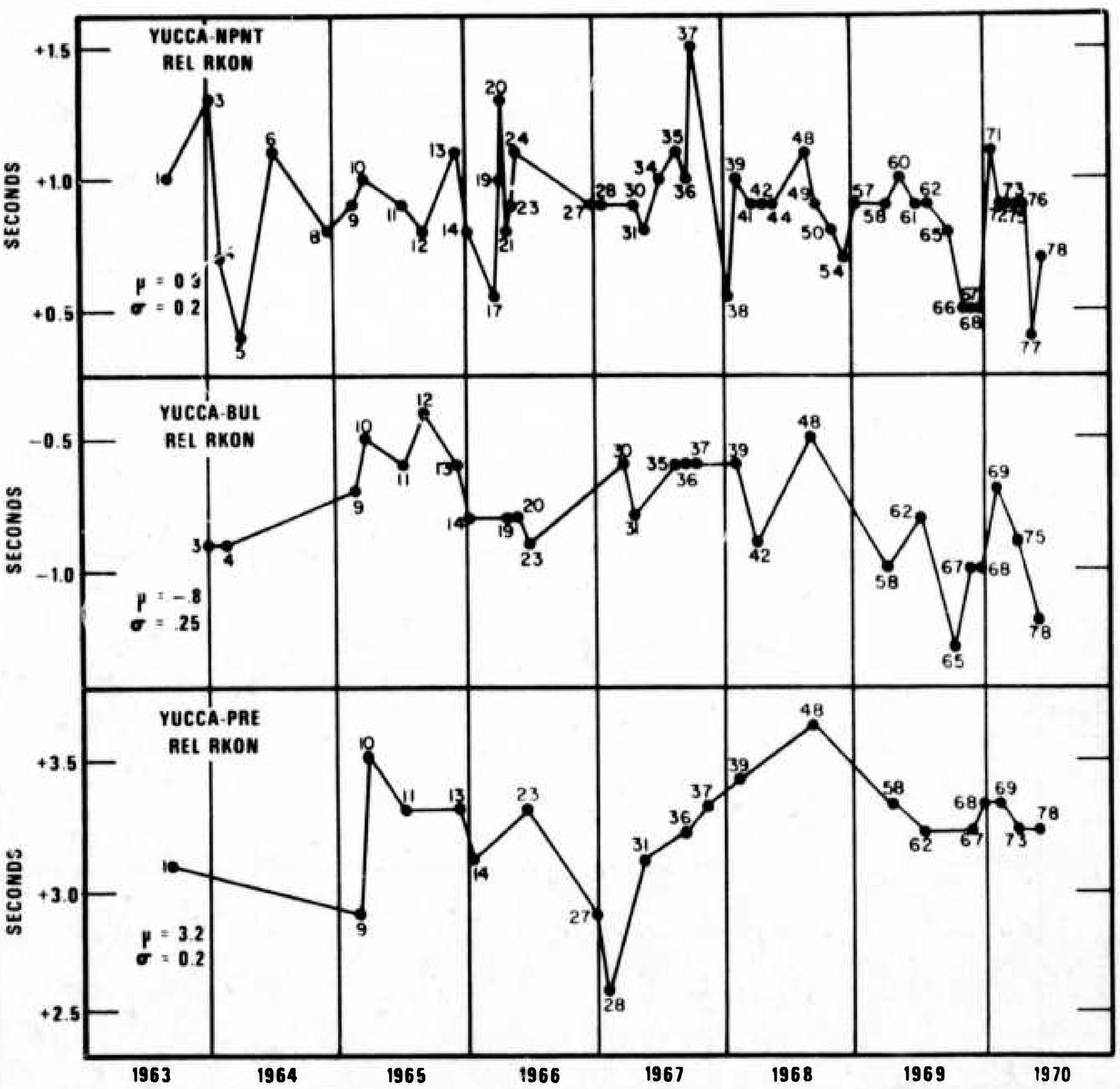

Figure 8. Yucca to NPNT, BUL, PRE, relative to RKON Herrin-68 residuals.

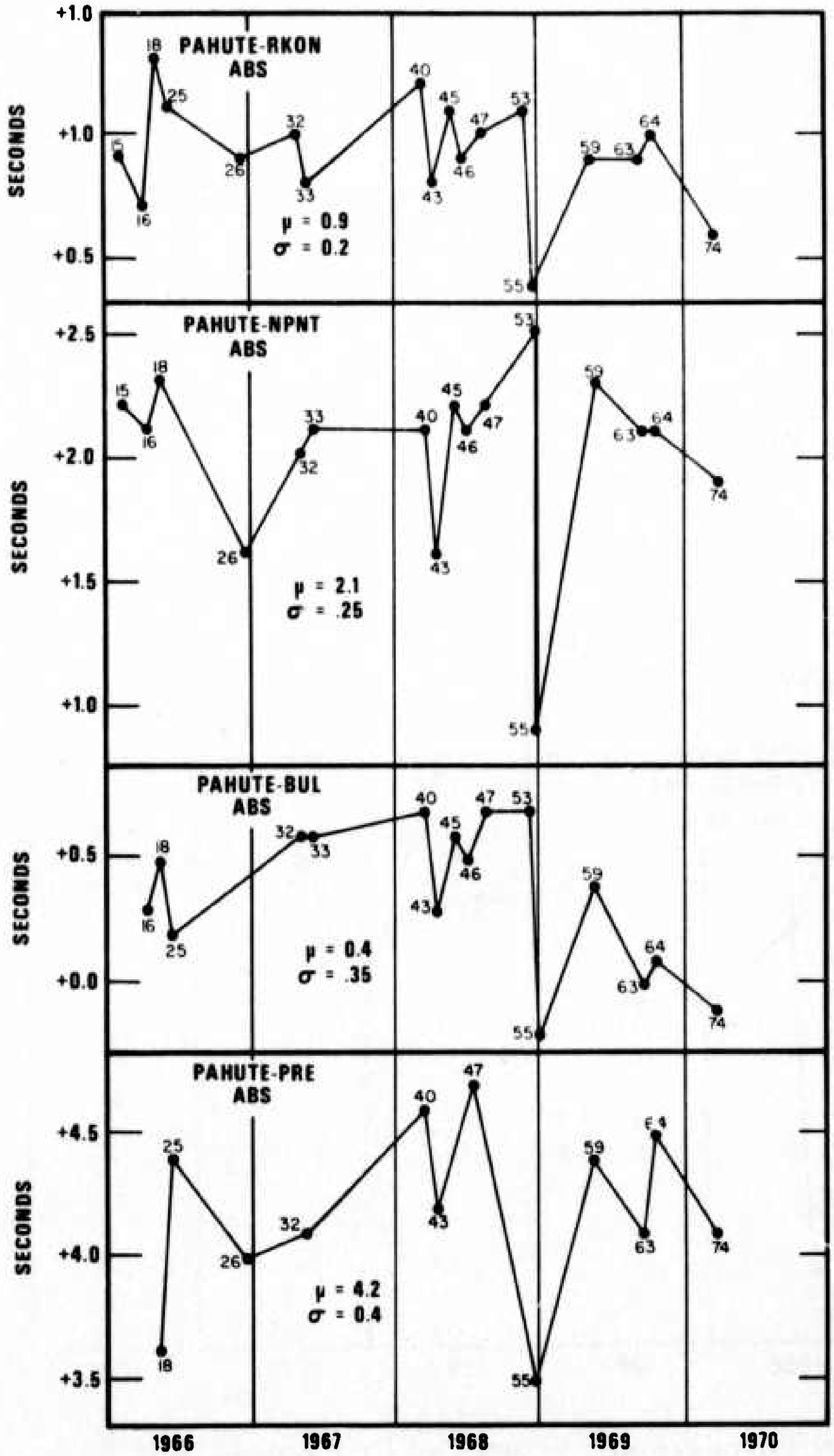

Figure 9. Pahute Mesa to RKON, NPNT, BUL, PRE absolute Herrin-68 residuals.

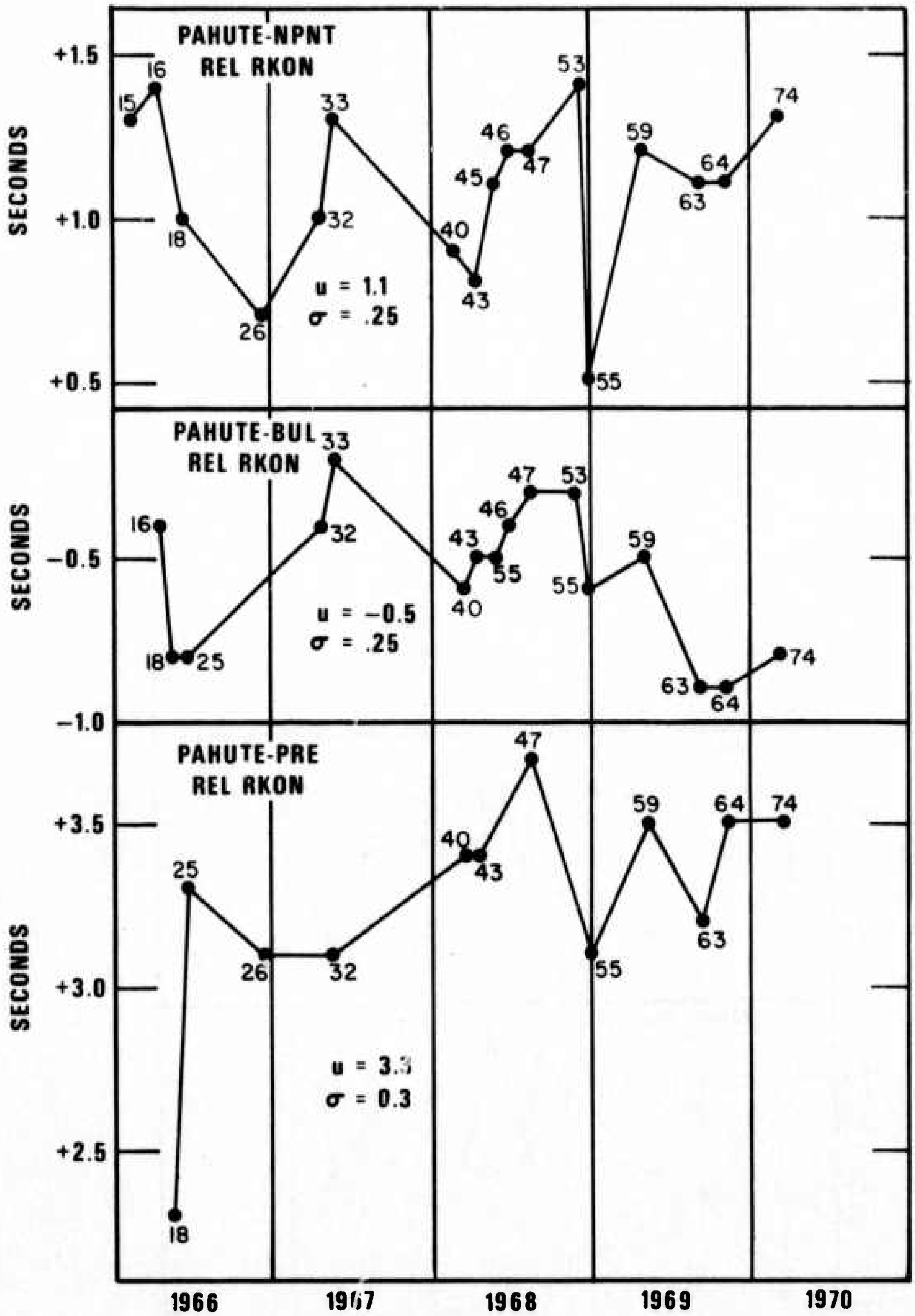

Figure 10. Pahute Mesa to NPNT, BUL, PRE relative RKON Herrin-68 residuals.

the 90% level although not at 95%. Since this is not a station effect, nor an effect of the variation of regional stress with time (since it was not observed for the Yucca explosions) we conclude that it may have something to do with variation of the geological structure under Pahute Mesa.

In Figures 11a,b,c we see contour map interpretations of the RKON and BUL residuals. Although it is not clear how one would perform a significance test of the hypothesis that the observations are correlated with location, it seems to the author that such a correlation exists. The existence of the pattern for relative residuals (Figure 11c) shows that it is not due to erroneous origin times or depths of burial since both of these effects would be expected to cancel out of relative residuals.

It is worth noting that for every station the variance of the travel-time residuals is greater for Pahute Mesa than for Yucca Flat events. This is in qualitative agreement with the arguments of Spence (1973) who studied the effect of an hypothesized igneous plug under Pahute Mesa by calibration of Pahute Mesa travel-time residuals against the apparently simpler patterns of DUMONT, a Yucca Flat event.

A possible explanation for the fact that the Pahute residual variation is smaller at RKON than at the other stations is that rays to RKON spend a smaller portion of their time in the high-velocity volcanic plug since they depart at a larger angle from the vertical than do the rays to more distant stations. Thus, depending on how close the event was to the center of the volcanic plug, the residuals to RKON and other stations would increase or decrease together; but with a different amplitude.

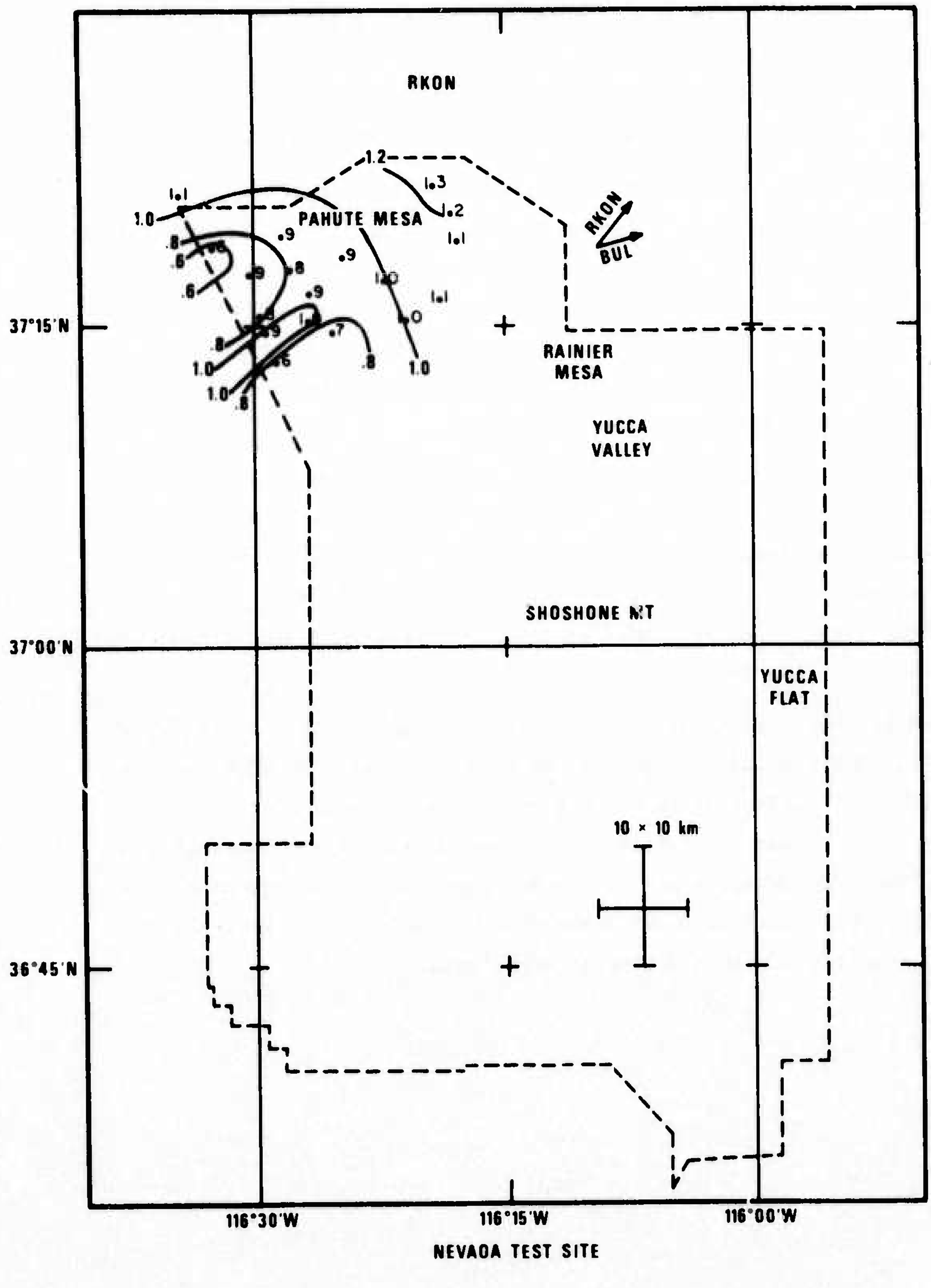

Figure 11a. Contours of RKON residuals for Pahute Mesa.

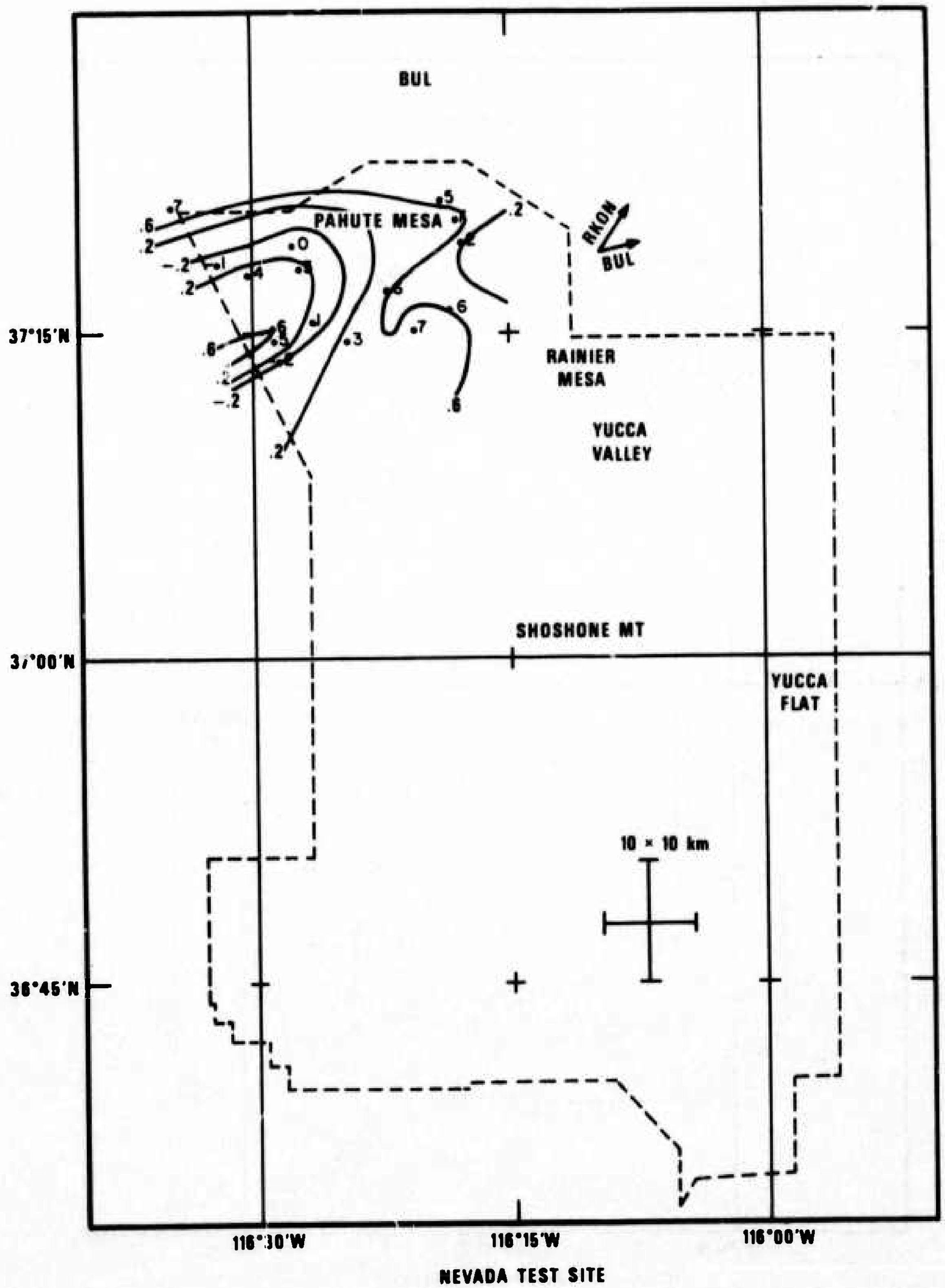

Figure 11b. Contours of BUL residuals for Pahute Mesa.

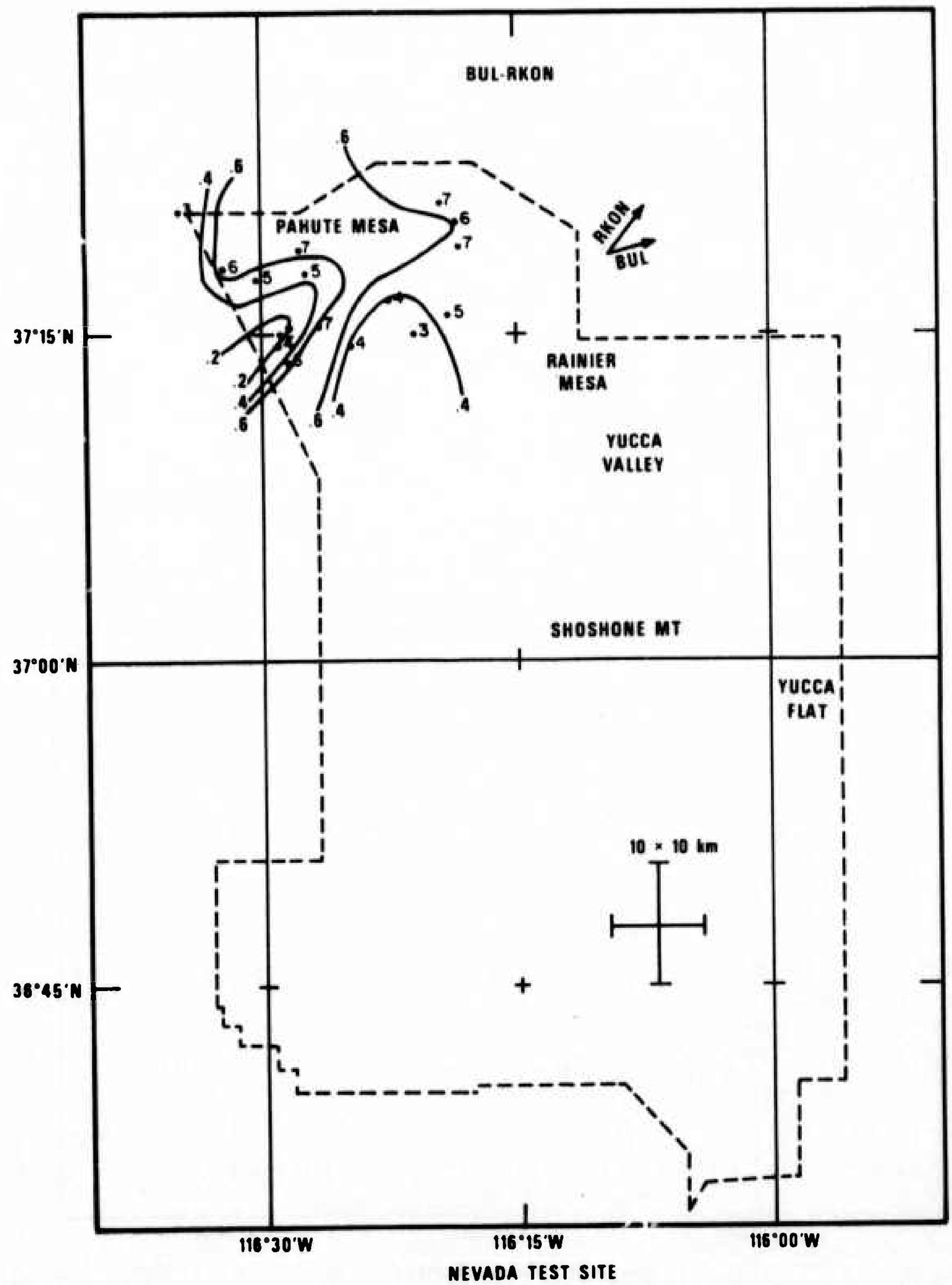

Figure 11c. Contours of BUL-RKON residuals for Pahute Mesa.

CONCLUSIONS AND POSSIBILITIES FOR FURTHER RESEARCH

Residuals obtained from NTS explosions constrained to their known depth and then located by standard Geiger methods may be used successfully to determine the depth of new shallow events. This represents confirmation of the results of Veith (1971, 1973, 1974, 1975) obtained with earthquake data. The standard deviation of 20-30 km for 5-9 station location of individual events suggests that depth determined using this technique will not be a reliable discriminant for weak events for depths less than 50 km.

There is no apparent variation of travel-time residuals with time for compressional waves from NTS to RKON, NPNT, BUL, or PRE. All of these stations are in essentially aseismic areas. It is conceivable that residuals to a station in a seismic area such as MAT in Matsushiro, Japan would exhibit a variation with time associated with the dilatancy effect, Wyss (1973).

Although one cannot reject the hypothesis that the mean Pahute Mesa residuals are the same as the mean Yucca residuals for RKON, NPNT, BUL or PRE, there is a substantially greater variation of travel-time residuals at each of these stations for events at Pahute Mesa than for events at Yucca. The variation appears to be correlated with location of the event, and is consistant with the hypothesis of Spence (1973) of more complicated structure under Pahute Mesa than under Yucca Flat. The standard deviation of travel-time residuals, even over as small a source region as Pahute Mesa can be as large as 0.4 seconds.

With respect to future work, we are presently studying the possibility of correcting travel-time residuals computed from deep earthquakes to the values they would have had had they been shallow events. The approach is to average P and pP residuals.

ACKNOWLEDGMENTS

The special arrival time measurements for RKON, NPNT, BUL and PRE were made by J. Gurski. M. Tillman and D. Racine performed most of the location calculations, and B. Schwartz modified program SHIFT into program SHIFT 360.

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